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Preliminary Technical Report

on

Item 1. Submicron Measurement Error Analysis.

Item 1 Work Statement: Evaluate the physical and metallurgical properties of materials used in measuring engine construction to determine comparative suitability to submicron measuring. Materials to be considered are: Meehanite, steel, granite, aluminum, magnesium, and glass.

Submitted by:

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Task II. Item 1. Preliminary Technical Report.

The materials under study are:

1. Meehanite
2. Steel
3. Granite
4. Aluminum
5. Magnesium
6. Glass

The materials may be more precisely defined as follows:

Meehanite. A high quality grey cast iron. The composition and properties are much more closely controlled than common structural cast iron. Meehanite is available in a variety of grades and the properties vary widely with grade.

Steel. Available in an enormous variety of alloys. For our purposes a low carbon, wrought, structural steel is representative.

Granite. Natural quarried granite is available in pink, grey, and black. Black granite is reportedly the hardest, most uniform, and best quality so we have used it in the evaluations.

Aluminum. Tooling plate is specially formulated and fabricated for high stability and low residual stresses. The cast type 300 is slightly better than wrought type. Therefore, the properties of Alcoa type 300 cast aluminum tool and jig plate have been used in the evaluation.

Magnesium. Dow Alloy AZ 31 B is specially fabricated in tooling plate with high stability and low residual stresses. Alloying elements are 1% zinc and 0.45% manganese.

Glass. Fuzed quartz was selected as the glass best suited to measuring engine applications.

The properties covered in detail in this preliminary report are:

1. Modulus of elasticity (stiffness).
2. Density (weight).
3. Ratio of stiffness to weight.
4. Thermal conductivity.
5. Thermal coefficient of linear expansion.
6. Thermal capacity.
7. Ratio of thermal expansion to thermal capacity.

1. <u>Modulus of Elasticity (stiffness), E.</u>

The modulus of elasticity is usually called Young's modulus and is a measure of the inherent stiffness of a material in tension or compression. It is the amount of force per unit area (stress in $lbs/inch^2$) required to affect a given deflection (strain in inches/inch). Since strain is a dimensionless ratio, the units of the modulus are in $lbs/inch^2$.

Typical values are:

Steel	29.0	$x\ 10^6$ psi
Meehanite (cast iron)	23.0 to 17.5	$x\ 10^6$ psi
Black Granite	13.6 to 8.4	$x\ 10^6$ psi
Aluminum tooling plate	10.3	$x\ 10^6$ psi
Magnesium tooling plate	6.5	$x\ 10^6$ psi
Fuzed quartz	4.4	$x\ 10^6$ psi

Steel is the stiffest of the common structural materials. The stiffness of Meehanite cast iron is different for the different grades but is consistent within a given grade. Granite being a natural unrefined material, the stiffness varies with the composition of the material as quarried.

2. <u>Density (weight), ρ.</u>

The lighter weight materials are desirable for structure in order to reduce the total weight of a machine and to reduce deflections of individual members due to their own weight.

Typical values are:

Magnesium tooling plate	.064 lbs/in^3
Fuzed quartz	.079 lbs/in^3
Aluminum tooling plate	.101 lbs/in^3
Black granite	.110 lbs/in^3
Meehanite cast iron	.257 lbs/in^3
Steel	.283 lbs/in^3

3. <u>Stiffness to Density Ratio, E/ρ.</u>

Normally, the lighter weight materials also have a lower stiffness modulus. Since it is desirable to have high stiffness and low weight for a given structure, the ratio of these two properties will give a figure of merit for the material. The units of the ratio are:

$$\frac{\text{Young's Modulus in } lbs/in^2}{\text{Density in } lbs/in^3} = \text{inches}$$

Typical values of E/ρ are:

Steel	102	$\times 10^6$ inches
Aluminum tooling plate	102	$\times 10^6$ inches
Magnesium tooling plate	102	$\times 10^6$ inches
Black Granite	77 to 123	$\times 10^6$ inches
Meehanite cast iron	68 to 89	$\times 10^6$ inches
Fuzed quartz	56	$\times 10^6$ inches

This interesting criterion shows that the design of a rigid structure will have the same weight regardless of whether steel, aluminum, or magnesium are selected for their inherent properties. Designing for a maximum stiffness-to-weight ratio, as required for most optical structures, is entirely different than designing for a maximum strength-to-weight ratio as is done in aircraft structure. Note also that granite, Meehanite, and quartz are less desirable materials from the standpoint of stiffness-to-weight ratio.

4. Thermal Conductivity, k.

The ability of a material to achieve a uniform temperature distribution throughout its volume in a minimum time is determined by its thermal conductivity. A high thermal conductivity is desirable if distortions of a structure due to a change in environment temperature are to be minimized. The thermal conductivity in cgs units is the amount of heat in calories which is transmitted per second through a plate one centimeter thick across an area of one square centimeter when the temperature difference is one degree centigrade. The thermal conductivity of pure copper, which is often used as a reference, is approximately 1.0 in cgs units.

Typical values are:

Aluminum tooling plate	.25 to .30	cgs
Magnesium tooling plate	.18	cgs
Steel	.15	cgs
Meehanite cast iron	.14	cgs
Fuzed quartz	.03	cgs
Black Granite	.005	cgs

5. Thermal Coefficient of Linear Expansion.

The amount that a bar of material will expand linearly under a specified temperature change is determined by the thermal coefficient of linear expansion. The units are expressed as strain in inches/inch per degree centigrade. A low coefficient is desirable to maintain dimensional stability of a structure as the temperature of the structure varies.

Typical values are:

Fuzed quartz	0.5	$\times 10^{-6}$ in/in/^{o}C
Black Granite	5.4	$\times 10^{-6}$ in/in/^{o}C
Aluminum tooling plate	12.0	$\times 10^{-6}$ in/in/^{o}C
Steel	12.0	$\times 10^{-6}$ in/in/^{o}C
Meehanite cast iron	12.0 to 12.4	$\times 10^{-6}$ in/in/^{o}C
Magnesium tooling plate	26.8	$\times 10^{-6}$ in/in/^{o}C

Since granite and Meehanite have roughly half the thermal coefficient of linear expansion of steel and aluminum and less than one-quarter that of magnesium, they are much more desirable in this respect for optical structures. Fuzed quartz is most desirable of all by a factor of 10 and more.

6. Thermal Capacity.

The amount of heat required to raise the temperature of a unit mass of material one degree C. is determined by its thermal capacity. The thermal capacity of water, which is the standard, equals one. The units are in calories per gram. This can be converted to BTU per lb or watt-seconds per lb if desired. Heat capacity is important when heat is being pumped into a structure for example, by a motor or a lamp. For optical structures it is desirable that the thermal capacity by high so that it can absorb heat with a minimum of temperature rise.

Typical values are:

Magnesium tooling plate	0.246 cal/gram/^{o}C.
Aluminum tooling plate	0.214 cal/gram/^{o}C.
Fuzed quartz	0.188 cal/gram/^{o}C.
Black Granite	0.172 cal/gram/^{o}C.
Meehanite cast iron	0.119 cal/gram/^{o}C.
Steel	0.115 cal/gram/^{o}C.

7. Ratio of Thermal Coefficient of Linear Expansion To Thermal Capacity.

The ratio of thermal expansion to thermal capacity indicates the amount of strain produced in a material by the absorption of a unit amount of heat. The units are strain in inches/inch divided by calories/gram which equals gram/calories.

The ratio is a truer indication of desirability of a material than either thermal expansion or thermal capacity taken alone. A low ratio is desired so that a maximum amount of heat can be absorbed with a minimum of strain resulting in the structure.

Typical values per gram of material are:

Fuzed quartz	2.7	$\times 10^{-6}$ in/in/cal
Black Granite	31.4	$\times 10^{-6}$ in/in/cal
Aluminum tooling plate	56.0	$\times 10^{-6}$ in/in/cal
Meehanite cast iron	100.9	$\times 10^{-6}$ in/in/cal
Steel	104.2	$\times 10^{-6}$ in/in/cal
Magnesium tooling plate	109.0	$\times 10^{-6}$ in/in/cal

Quartz clearly has the best thermal properties while Meehanite, steel, and magnesium are all about the same. Black granite is about three times as thermally stable and aluminum is about twice as thermally stable as the other metals. Thus, the rankings of desirability have changed compared to that obtained by considering only the thermal expansion coefficient.

8. Other Properties.

The strength of the materials under study is not a major consideration. In a structure designed for maximum rigidity the stresses are low.

The ductility (or its inverse, brittleness) of the materials is important as related to manufacturing ease and rough handling in use. Manufacturing ease will be discussed separately.

The damping characteristic of the materials is of considerable importance in optical structures, but data are essentially unavailable. A high damping factor is desirable so that the material will absorb or attenuate vibrations and prevent them from ringing through the structure. Certain construction techniques can be used to provide a dead or well damped structure. Construction techniques will be discussed separately at a later date.

One of the attributes claimed for magnesium, for granite, and for Meehanite is their high damping coefficients. Steel, of course, rings like a bell. Since this characterisitic is of importance, a further search will be made for data.

Corrosion resistance is also an important characteristic. Quartz and granite do not corrode under normal laboratory conditions and require no protection. Aluminum also requires no corrosion protection for measuring engine application. Its oxide forms a hard, tough impervious coating. Steel and Meehanite corrode readily and continuously unless well protected by paint, oil, or grease.

Magnesium is highly susceptible to corrosion and difficult to protect. Dow has developed special finishes and treatments for corrosion protection of magnesium alloys. It is almost impossible, however, to protect clean working surfaces and the magnesium oxide is a fine, white, loose powder which can contaminate bearings and sliding surfaces.

Dimensional stability of the materials is of great importance but data are almost non-existent. Quartz and granite have excellent dimensional stability. For the metals, good stress relief treatments are essential to achieve good dimensional stability. Of the metals, cast iron is considered to have the best dimensional stability and aluminum jig plate next. The standing of steel and magnesium tooling plate is undetermined. Further search will be made for data on dimensional stability.

9. Fabrication.

Quartz is a non-structural material because of its high cost and extreme difficulty of fabrication. It can be shaped only by casting, sawing, grinding, sand blasting, or chipping. It can be joined only by clamping or fuzing. It cannot be threaded, riveted, or bolted without special precautions. It cannot be machined or welded.

Granite has all the same limitations and it cannot be cast. Its cost is so low, however, that it is economic to use it in large blocks as in surface plates.

Magnesium can be readily cast, machined, sawed, threaded, riveted, and bolted. It is seldom welded and in machining special safety precautions must be taken. Its cost is higher than the other metals, and it is more expensive to fabricate.

Meehanite can be cast, machined, and joined by all common methods. Due to abrasive tool wear, machining is a little slow and, therefore, a bit expensive. The basic castings, however, are inexpensive.

Aluminum can be cast, machined, and joined by all the common methods. The material cost is more expensive than steel or cast iron but machining is fast and cheap.

Steel is the most common structural material and generally the cheapest. It can be cast machined and joined by all common methods.

10. Summary.

For design of high stiffness to weight structures, as is required in most optical equipment, steel, aluminum, magnesium and certain formulations of Meehanite are equally efficient. The light weight advantage of magnesium and aluminum disappears when the modulus of elasticity is taken into account (see column 3 of Summary Tabulation). Magnesium is least desirable when its corrosion and cost are considered. Steel is most desirable from its cost and ease of fabrication, but aluminum has some advantage in its very high thermal conductivity which tends to reduce thermal distortions. When lamps and motors are involved, they act as localized heat sources and pump heat into the structure causing temperature gradients. Under such conditions, aluminum is the most desirable structural material.

When the principal limitation is space, not weight, steel is clearly the most desirable.

For design which requires optical flatness and straightness and no thermal expansion, quartz is the most desirable. Granite is second but is not as good as quartz by a factor of 10. The cost and availability of quartz restricts its use unless the design can be arranged to use only small sections. Aluminum is third but is not as good as granite by a factor of 2. Meehanite, steel, and magnesium are all about the same, but are not as good as aluminum by a factor of 2.

11. <u>Additional Work</u>.

Further data on damping, ductility, and dimensional stability will be obtained and presented in a later report. The numerical effect of material properties on submicron measuring will be investigated and the design approach necessary to maximize the advantages of the materials will be considered.

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Summary of Tabulation of Physical and Metallurgical Properties
of Six Materials Ranked in Order of Their Desirability
for a Submicron Measuring Machine

1.	Modulus of Elasticity (Stiffness) E	2.	Density (Weight)	3.	Stiffness/Weight E/ρ	4.	Thermal Conductivity
	10^6 psi		lbs/in.^{3}		10^6 inches		cal/sec/cm/cm^2/^{o}C.
1.	Steel 29.0	1.	Magnesium .064	1.	Steel 102	1.	Aluminum .25 to .30
2.	Meehanite 23.0 to 17.5	2.	Quartz .079	1.	Aluminum 102	2.	Magnesium .18
3.	Granite 13.6 to 8.4	3.	Aluminum .101	1.	Magnesium 102	3.	Steel .15
4.	Aluminum 10.3	4.	Granite .110	1.	Granite 77 to 123	4.	Meehanite .14
5.	Magnesium 6.5	5.	Meehanite .257	2.	Meehanite 68 to 89	5.	Quartz .03
6.	Quartz 4.4	6	Steel .283	3.	Quartz 56	6.	Granite .005

Summary of Tabulation of Physical and Metallurgical Properties
of Six Materials Ranked in Order of Their Desirability
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5.	Thermal Coefficient of Linear Expansion		6.	Thermal Capacity		7.	Ratio Thermal Expansion/ Thermal Capacity	
	10^{-6} in./in./°C.			cal/gram			10^{-6} in./in./cal	
1.	Quartz	0.5	1.	Magnesium	.246	1.	Quartz	2.7
2.	Granite	5.4	2.	Aluminum	.214	2.	Granite	31.4
3.	Aluminum	12.0	3.	Quartz	.188	3.	Aluminum	56.0
3.	Steel	12.0	4.	Granite	.172	4.	Meehanite	100.9
4.	Meehanite	12.0 to 12.4	5.	Meehanite	.119	5.	Steel	104.2
5.	Magnesium	26.8	6.	Steel	.115	6.	Magnesium	109.0